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Climate-smart management can further improve winter wheat yield in China

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ABSTRACT

Climate change, genotype, and agronomic management have profound impacts on crop yield. Our goal in this study is to untangle the interrelated contributions of climate change, genetic improvements, and agronomic management on winter wheat yield in China to develop management strategies that address future nutritional needs. The Agricultural Production System Simulator (APSIM) farming systems model was used to simulated long-term (1981–2010) wheat yield for four wheat production regions under different Genotype by Environment by Management (GxExM) scenarios. Using detailed field experimental data from 1981 to 2005 in conjunction with the APSIM-wheat model, the potential for climate-smart management to improve yield on a regional scale is investigated. Results showed that when all climatic variables were considered together, winter wheat relative yield change decreased from 0.62% to 7.16% over the period 1981 to 2010, depending on cultivar and growing region. The impact of individual climatic variables varied by region. In general, winter wheat yields showed the least decline in the Northern China Plain (NC) due to climate change. Cultivar renewal combined with improvements in agronomic management boosted yields but to a different extent in each region. For cultivar renewal, yields increased 6.93%, 17.69%, 24.87%, and 52.72% in the NC, Yellow and Huai River Valleys (YH), SW and YV, respectively over the period 1981 to 2010. Agronomic management improved yields by 22.91%, 5.27%, 58.77%, and 59.20% in these regions, respectively. Overall, the observed yield improvements with agronomic management were higher than those resulting from cultivar renewal for most of China's wheat growing regions. The exception was found in YH, where improvements in winter wheat yield from cultivar renewal were greater than those from agronomic management. Regardless, there is still ample room for yield improvement in winter wheat by implementing climate-smart management. SW would benefit significantly, with a potential increase of 99% because of improved agronomic management. More moderate, but still significant increases were predicted for NC and YH (49% and 42%, respectively) while only moderate improvements were anticipated for YV (17%). Our findings highlight the extent that improvements in cultivar renewal and agronomic management have compensated for the negative impacts of climate change for different wheat growing regions of China over the past three decades. The results also indicate that advances in agronomic management outweighed the effects of cultivar renewal in most regions. Climate-smart management is still needed to further improve yields in wheat-growing regions of China.

1. Introduction

Improvements in crop yields have slowed since the 1990s (Evenson and Gollin, 2003; Rosegrant and Cline, 2003) and even stagnated in much of the world since the last century (Finger, 2010; Fischer and Edmeades, 2010; Grassini et al., 2013; Hafner, 2003; Ray et al., 2012). The stagnation or collapse of crop yields has profound implications for global food systems (Ray et al., 2012). Indeed, continued crop yield improvements are required to feed the world in the 21st century (Cassman, 1999; Rosegrant and Cline, 2003; Tester and Langridge, 2010). Accordingly, substantial research efforts have been directed towards quantifying the contributions of the drivers (e.g. climate change, genotype, and agronomic management) to crop productivity and their subsequent effects on yield improvements for both China (Bai et al., 2015; Xiao and Tao, 2014) and internationally (Fischer et al., 2009; Kirkegaard and Hunt, 2010).

Climate is the major uncontrollable factor that influences crop yield and has been accepted as one of the factors contributing to yield stagnation globally (Godfray et al., 2010; Hochman et al., 2017; You et al., 2009). Several studies documented that temperature increases since the

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1980s have reduced crop yields by accelerating phenological development, shortening the duration of crop growth and grain filling period, aggravating heat-related water stress, and exacerbating pest and disease losses (Lobell et al., 2013; Xiao et al., 2013). Improvements in crop cultivars and agronomic management practices had somewhat alleviated the negative impacts of climate change and helped to maintain continued increases in crop yields (Wang et al., 2012b). The interactions between climate change, genotype, and agronomic management are quite complicated and vary substantially between regions and cropping systems. To improve our understanding of climate change impacts and develop adaptation options, it is necessary to isolate the contributions of climate change, the impacts of each climate variable, genotypic improvements, and modern agronomic management to the observed changes in crop yield (Bai et al., 2015).

Information technology has the potential to improve agricultural production through the integration of knowledge to deliver improved management options to producers (Sassenrath et al., 2008). Climate-smart management can favorably increase yield and improve food security, which could be defined as an optimal management practice.

Empirical analysis is recognized as a widely-used approach for quantifying environmental and managerial contributions to yield gains, using historical data on crop yields, investments, and environments to train specific regression equations (Lobell and Asner, 2003; Xiong et al., 2014; You et al., 2009). In spite of limited reliance on detailed field data for statistical methods to detect the effects of different drivers (Lobell and Burke, 2010), empirical analysis still showed a limited ability to mechanistically interpret and explain the observed yield stagnation (Xiong et al., 2014). Additional methods to delineate the causes of yield trends are needed. Process-based crop growth models are commonly used to quantify the impacts of environment and agronomic management on crop yields (Li et al., 2015; Liu et al., 2010; Xiao and Tao, 2014; Zhang et al., 2013). Because of the ability to repeat and simulate a range of management scenarios, crop models are capable of evaluating the effectiveness of different agricultural management (or adaptation) strategies (Xiong et al., 2014). The Agricultural Production System Simulator (APSIM) model is now being used in over 110 countries around the world (Gaydon et al., 2017; Hochman et al., 2017; Keating et al., 2003) and has been widely tested and applied to crop studies in China (Chen et al., 2010; Li et al., 2015; Liu et al., 2010; Sun et al., 2015; Xiao et al., 2017). It is a component-driven model with several simulation modules including crop growth and development, soil water and nitrogen dynamics developed by the Agricultural Production Systems Research Unit of Australia (Holzworth et al., 2014). APSIM has evolved towards a new generation of agricultural systems simulation since its inception and the enhanced APSIM model can be used to simulate a wide range of combinations of Genotype by Environment by Management (GxExM) scenarios to assess the effect of changed cultivars and so on (Holzworth et al., 2014; Ridoutt et al., 2013).

Wheat is a vital cereal crop in China, which is grown on 24.7% of the cultivated land accounting for 21.2% of total Chinese grain production (National Bureau of Statistics of China, 2015). Winter wheat accounts for 91.0% of the total wheat yield and 87.5% of the area planted to wheat (National Bureau of Statistics of China, 2015). In the past several decades, actual wheat yield in China has improved due to the combined effects of climate change, cultivar renewal, improved agronomic management practices, and technological advancement (Qin et al., 2015). However, it is challenging to maintain a rapid and consistent rate of yield improvement all the time. Identifying the causal factors contributing to yield improvements in winter wheat in China has become increasingly important in the development of realistic management protocols to maintain and improve future yield goals. Many studies have investigated the roles of climate, cultivar, and management on winter wheat yield changes (Bai et al., 2015; Xiao and Tao, 2014), but primarily at a station level with few studies addressing regional yield shifts.

In this study, our goal is to untangle the contributions of climate change, cultivar renewal, and agronomic management on past winter wheat yield growth for the four primary wheat production regions of China under different Genotype by Environment by Management (GxExM) scenarios during the period from 1981 to 2010. We use detailed experimental data from 1981 to 2005 together with the evaluated APSIM-wheat model at a regional scale to delineate causal relationships between environment, cultivar, management and wheat yield. These results are then used to investigate the potential improvements in yield that would be possible through implementation of climate-smart management on a regional scale.

2. Materials and methods

2.1. Study areas

Winter wheat is planted under diverse geographic and climatic conditions across China. A previous study (Jin, 1991) classified the winter wheat-growing areas of China into six physiogeographic regions: the Northern China Plain (NC); the Yellow and Huai River Valleys (YH); the Middle and Lower Yangtze Valleys (YV); Southwestern China (SW); Xinjiang (XJ); and Southern China (SC) (Fig. 1). In this study, research was concentrated on the four major winter wheat regions (NC, YH, YV and SW) that produce > 90% of China's wheat.

2.2. Sources of data

The climate data set for this study was obtained from 205 weather stations from the China Meteorological Data Sharing Service System (http://cdc.cma.gov.cn/), selected based on the length of time series and data integrity (Fig. 1). The weather station data include the daily minimum and maximum temperatures, sunshine hours, average relative humidity, wind speed, and rainfall from 1981 to 2010. The data quality control practices for these climate variables were implemented by the China Meteorological Administration. Actual solar radiation measurements were not available at most of the stations, thus sunshine hours were converted to daily solar radiation using the Angstrom formula (Black et al., 1954; Jones, 1992).

Crop data on winter wheat phenology were obtained from field trials at the Agro-meteorological Experimental Stations operated by the China Meteorological Administration. The experimental station data on winter wheat phenology (sowing, emergence, flowering, and maturity dates), cultivar type, yield, biomass, and management practices (planting density, irrigation, and fertilizer) used in this study were

Fig. 1. Physiogeographic wheat production regions and weather recording stations in China. The four winter wheat producing regions of China are identified with labels: NC, Northern China Plain; YH, Yellow and Huai River Valleys; YV, Middle and Lower Yangtze Valleys; SW, Southwestern China. The grey solid points in the figure indicate the location of the weather stations used in this study.

Table 1
Details on the cultivars and agronomic management practices used in each region for 1981–1989(80s) and 2001–2009(00s) in the study.

Region	North China Plain (NC)		Yellow and Huai river valleys (YH)		Middle and lower Yangtze Valleys (YV)		Southwestern China (SW)	
Cultivar	80s	00s	80s	00s	80s	00s	80s	00s
Name	Jinfeng1	Zhongmai9	Jinan13	Lumai21	Boai7023	Yumai18	Datouhuang	Simaizao
Calibration dataset	Wang et al.2012	1996–1998 in Luancheng	1981–1982 in Zibo; 1981 in Weifang; 1981–1982 in Linyi	2001–2002 in Laiyang; 1998–2000 in Linyi	1981–1984 in Gushi	2000–2002 in Gushi	1983–1984 in Tongren; 1981 in Zhengan	1996,1998,2000 in Tongren
Evaluation dataset	Wang et al.2012	1999,2000,2003 in Luancheng	1981 in Heze;1981–1982 in Laiyang;1982–1983 in Zibo;1982–1983 in Weifang	2002–2004 in Laiyang; 2000–2001 in Zibo	1985–1989 in Gushi	2003–2005 in Gushi	1985 in Tongren;1984–1986 in Zhengan	2001,2002,2005 in Tongren
SD (Month-Day)	10–1	10–4	9–29	10–8	9–29	10–8	10–19	11–3
PD (Plant m^{-2})	650	470	350	510	750	460	400	330
BF (kg N ha^{-1})	35	130	150	135	100	135	75	75
JF (kg N ha^{-1})	105	210	70	100	–	–	–	70
Irrigation (mm)	45	40	52.5, 60, 60	52.5, 67.5, 60	–	–	–	–
time	1, 2, 3, 5	1, 2, 3, 6	2, 4, 6	1, 2, 4				
Vern_sens	2.7	3.7	2.3	3.0	3.25	1.3	3.3	3.05
Photo_sens	3.3	3.9	3.0	3.1	3.15	2	3.3	2.9
Startgf_to_mat	420	597	560	570	540	560	550	790
Grain_per_gram_stem (kernel g $stem^{-1}$)	23.0	25.0	22.0	30.0	21.0	25	25.0	38
Max_grain_size(kg)	0.041	0.038	0.040	0.045	0.020	0.040	0.025	0.026
Potential_grain_filling_rate (g $grain^{-1}$ day^{-1})	0.0025	0.0025	0.0022	0.0032	0.0015	0.0022	0.025	0.065

NC, the Northern China Plain; YH, the Yellow and Huai River Valleys; YV, the Middle and Lower Yangtze Valleys; SW, Southwestern China. SD is sowing date, PD is planting density, BF is Base Fertilization, JF is Jointing Fertilization. The irrigation timeline: 1, from seeding to before winter freezing; 2, from regrowth to jointing; 3, from jointing to booting; 4, from booting to heading/flowering; 5. from flowering to milking; 6. from milking to maturity.

measured from 1981 to 2005.

2.3. APSIM-wheat model

The APSIM-wheat model can simulate daily crop development, growth, and biomass production. Detailed information on the APSIM-wheat model structure and processes are available at http://www.apsim.info, and the capabilities of APSIM-wheat version 7.6 used in this study are documented by Holzworth et al. (2014). It has been successfully tested in numerous studies and shows a high degree of congruence with observed crop growth and yield (Mohanty et al., 2012).

The APSIM-wheat model was calibrated and evaluated respectively in four wheat production regions using a trial-and-error method under different Genotype by Environment by Management (GxExM) scenarios based on the Agrometeorological Experiment station data from 1981 to 2005 (Table 1 and Fig. S1). The obsolete (80s) and modern (00s) cultivars were selected for each region based on the cultivar planted the longest within each region, which reflected the plant acclimation and adaptation of the local cultivars to the environment and hence were representative of the specific areas during the specific period of interest. The cultivar-specific parameters required to run the APSIM-wheat model included the crop development control parameters and the crop productivity control parameters, and were adjusted during the model calibration process (Table 1). The crop development control parameters included vern_sens (sensitivity to vernalization), photop_sens (sensitivity to photoperiod), and tt_startgh_to_mat (thermal time from beginning of grain filling to physiological maturity, °C day). The vern_sens parameter and photop_sens parameter together determined the development rate (time) from the end of the juvenile phase to the floral initiation phase. These two parameters were associated with the flowering date. The crop productivity control parameters included grain_per_gram_stem (coefficient of kernel number per stem weight at the beginning of grain filling, kernel g $stem^{-1}$), potential_grain_filling_rate (potential grain-filling rate, g $grain^{-1}$ day^{-1}), and max_grain_size (the maximum weight per grain, g) (Table 1). Statistical indicators of the coefficient of determination (R^2), root mean square error (RMSE), normalized root mean square error (NRMSE), and Willmott's index of agreement (*D*-values, Willmott, 1982) were used to evaluate model performance on the days to flowering dates, maturity dates, and yield for each cultivar selected in the study.

2.4. Experimental design

In this study, modeling experiments were set up to delineate the impacts of different climate variables (Table 2), crop cultivars (Table 3, S1 and S3), agronomic management (Table 3, S2 and S3) and the role of climate-smart management (Table 3, S3 and S4) on winter wheat yield.

2.4.1. Quantifying the impacts of different climate variables on yield change

Three modeling experiments were conducted to delineate the impacts of different climate variables on winter wheat yield from 1981 to 2010 (Table 2) under the optimal simulation experiment S4 in Table 3. The model was first run with all climatic variables together, and then with temperature and solar radiation measurements individually modified to delineate total climate impacts, and individual (temperature or radiation) impacts. To estimate the impact of changes in all the climate variables on wheat yield, the model simulated wheat growth and yield from 1981 to 2010 using the 30-year time series of observed

Table 2
Simulation experiments and the input data used to delineate the impact of different climate variables on winter wheat yield.

Climate variable	Temperature	Radiation	Precipitation
Con_all	1981–2010	1981–2010	1981–2010
Con_temp	1981–2010	1981	1981
Con_rad	1981	1981–2010	1981

Con_all, Con_temp, and Con_rad represent the modeling experiment on the impacts of all climate variables, and temperature and solar radiation individually on winter wheat yield, respectively.

Table 3
Simulation experiments used to evaluate the contributions of cultivar renewal and agronomic management to winter wheat yield change.

Experiment	Climate	Cultivar	Management	Soil
S1	1981–2010	80s	00s	Actual
S2	1981–2010	00s	80s	Actual
S3	1981–2010	00s	00s	Actual
S4	1981–2010	00s	Optimal	Actual

climate data from 1981 to 2010 and the impacts were then estimated following Eq. (1). To disentangle the impact of change in temperature on crop yield, the model was run from 1981 to 2010 with observed daily temperature from 1981 to 2010 and the observed daily solar radiation and precipitation held constant at the level observed in 1981. Likewise, the impact of change in solar radiation on crop yield was estimated using daily radiation data from 1981 to 2010 and with daily temperature and precipitation held constant at the levels recorded in 1981. The relative yield change due to the change of all the climate variables combined as well as temperature and solar radiation individually were calculated as follows (Asseng et al., 2016):

$$\text{Relative yield change (\%)} = \frac{(Y_s - Y_b)}{Y_b} \times 100\% \tag{1}$$

where Y_S is the yield simulated in the three simulation experiments, and Y_b is the simulated baseline yield (Year = 1981).

2.4.2. Quantifying the contributions of crop cultivars and agronomic management on yield change

In this study, three modeling experiments (S1, S2, and S3) were set up in a continuous wheat simulation from 1981 to 2010 to evaluate the impacts of cultivar renewal and agronomic management on winter wheat yield (Table 3). Briefly, the sowing date, planting density, nitrogen fertilizer rules, and irrigations were set to emulate the management practice for farmers that were available and widely recommended during the specific period for the representative cultivar we selected. The actual soil data were input into the soil module for all the stations in each region. The soil data from the China Soil Scientific Database included the soil bulk density (BD), drained upper limit (DUL), 15 bar lower limit (LL15), total nitrogen (N), soil organic carbon (SOC) and pH value (pH) in 0–150 cm soil layers (Table 4). The detailed information about how cultivar and agronomic management parameters from the field data integrated into the model was shown in Table 1.

The contribution of cultivar renewal to winter wheat yield was disentangled by comparing modeling experiments S3 and S1. The contribution of cultivar renewal on winter wheat yield was calculated as:

$$C_{Cul} = \frac{Y_{S3} - Y_{S1}}{Y_{S1}} \times 100\% \tag{2}$$

where $C_{\mathrm{Cul}}$is the contribution of cultivar renewal to yield, %; Y_{S3} and $Y_{S1}$are respectively the simulated yields in experiments S3 and S1, kg ha^{-1}.

Similarly, by comparing S3 and S2, the contribution of new agronomic management to winter wheat yield was calculated as:

$$C_{Ma} = \frac{Y_{S3} - Y_{S2}}{Y_{S2}} \times 100\% \tag{3}$$

where $C_{\mathrm{Ma}}$is the contribution of agronomic management to yield, %; Y_{S3} and $Y_{S2}$are respectively the simulated yields of experiments S3 and S2, kg ha^{-1}.

2.4.3. Quantifying the role of climate-smart management

Climate-smart management in this study was defined as an optimal management practice. The concept of climate-smart management should be given comprehensive consideration at sowing, timely adequate control at each critical growth period (e.g. group structure and control), compensation practices at vulnerable periods, and protective control measures at sensitive periods. In this study, a fourth simulation (S4) was run to determine the impact of optimal management (climate-smart management) on wheat yield (Table 3). In modeling experiment S4, the simulations for each region were set up with the modern (00s) cultivar using the daily weather records from 1981 to 2010 in a continuous wheat simulation. Water and fertilization applications were set as non-limited. Optimum planting density and the theoretic optimal planting date was used and changed annually depending on the active accumulated temperature (Liu and Li, 2010; Wang et al., 2012a) and the optimum temperature from sowing to emergence (Gong, 1988). The optimal soil data were input into the soil module for all the stations in each region. The method to estimate the theoretic optimal planting date and the optimal soil was shown in the Supplementary Materials. The potential improvement of the yield due to the climate-smart management was calculated as:

Table 4
Range of soil profile properties across the primary winter wheat growing regions in China.

Region	Soil layer depth (cm)	Bulk density (BD, g cm^{-3})	Drained upper limit (DUL, mm mm^{-1})	15Bar lower limit (LL15, mm mm^{-1})	Total N (%)	pH value	Soil organic carbon (SOC, %)
NC	0–10	1.15–1.64	0.17–0.48	0.07–0.33	0.01–0.13	6.0–9.0	0.08–3.19
	10–20	1.18–1.55	0.14–0.48	0.05–0.33	0.01–0.13	5.9–9.0	0.08–3.19
	20–30	1.28–1.58	0.14–0.47	0.05–0.36	0.01–0.13	5.8–9.1	0.08–2.91
	30–70	1.26–1.57	0.16–0.47	0.05–0.34	0.01–0.08	5.7–8.9	0.08–2.19
	70–150	1.15–1.62	0.13–0.46	0.06–0.37	0.00–0.05	5.7–8.9	0.05–2.55
YH	0–10	0.95–1.67	0.15–0.50	0.07–0.36	0.00–0.17	5.2–9.2	0.13–4.62
	10–20	0.95–1.67	0.15–0.49	0.07–0.37	0.00–0.11	5.2–9.7	0.13–2.88
	20–30	0.95–1.69	0.17–0.48	0.08–0.41	0.00–0.07	5.3–9.5	0.09–1.14
	30–70	0.96–1.71	0.19–0.56	0.07–0.55	0.00–0.06	5.5–9.3	0.08–1.15
	70–150	1.02–1.71	0.15–0.45	0.09–0.35	0.00–0.04	5.3–9.0	0.05–0.79
YV	0–10	0.81–1.43	0.17–0.54	0.08–0.43	0.01–0.14	4.4–10	0.26–3.31
	10–20	0.99–1.58	0.13–0.54	0.07–0.43	0.01–0.14	4.5–10	0.15–3.13
	20–30	1.11–1.65	0.11–0.56	0.06–0.51	0.01–0.18	4.4–9.2	0.10–4.91
	30–70	1.11–1.64	0.11–0.54	0.06–0.49	0.01–0.25	4.5–9.1	0.08–6.83
	70–150	1.11–1.68	0.13–0.52	0.07–0.44	0.00–0.11	4.5–9.1	0.07–2.80
SW	0–10	0.81–1.53	0.2–0.54	0.09–0.46	0.01–0.24	4.1–8.2	0.19–6.53
	10–20	0.81–1.62	0.2–0.53	0.1–0.48	0.01–0.20	4.1–8.3	0.19–5.35
	20–30	0.90–1.83	0.19–0.53	0.09–0.48	0.01–0.13	4.1–8.6	0.17–3.60
	30–70	1.01–1.83	0.2–0.53	0.1–0.5	0.01–0.13	4.1–8.6	0.05–3.18
	70–150	1.01–1.83	0.18–0.54	0.09–0.51	0.00–0.13	4.1–8.7	0.03–3.15

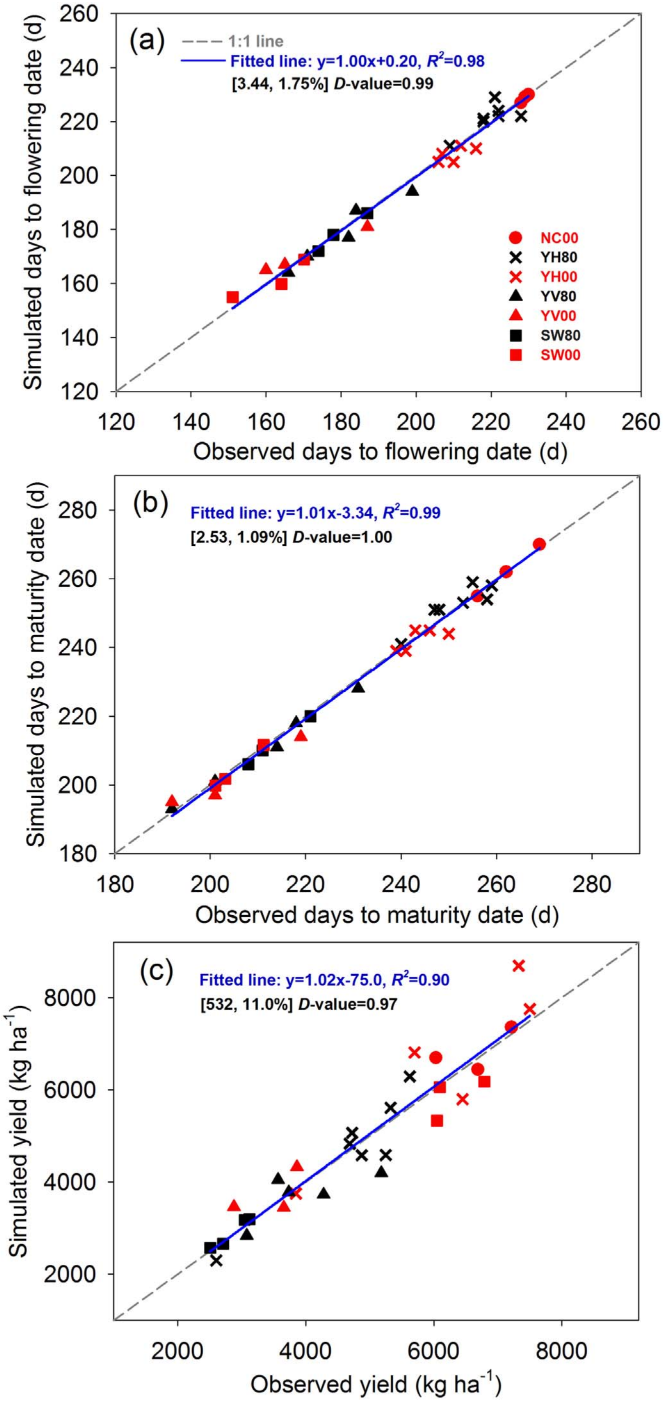

Fig. 2. Evaluation of the APSIM-Wheat model simulation for days to flowering (a), days to maturity (b), and yield (c) in the four study regions. Different shapes indicate the individual study regions and different colors indicate different cultivars. For example, YH80 in black indicates cultivar-80 in the Yellow and Huai River Valleys and YH00 in red indicates cultivar-00 in the Yellow and Huai River Valleys. Regression equations were fit to all values, with R^2 as given. Numbers in the square brackets refer to the values of RMSE and NRMSE, respectively, followed by D-values. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

$$A_{SM} = \frac{Y_{S4} - Y_{S3}}{Y_{S3}} \times 100\% \tag{4}$$

where A_{SM} is the potential improvement in yield due to the climate-smart management, %; Y_{S4} and Y_{S3} are respectively the simulated yields of experiments S4 and S3, kg ha^{-1}.

3. Results

3.1. APSIM-wheat model evaluation performance

The evaluation performance was shown in Fig. 2. The results showed that the simulated days to flowering and maturity were in good agreement with the observed days for wheat in the four regions (Fig. 2). The R^2 values for days to flowering and days to maturity were 0.98 and 0.99, and the D-values were 0.99 and 1.00, respectively, whereas the simulated deviations derived from the RMSE values were 3.44 days and 2.53 days, respectively (Fig. 2). In addition, simulated yields were well matched with observed yields (R^2 = 0.90, D-values = 0.97). Overall, the APSIM-wheat model simulated the phenological development and yield information for all cultivars at all locations with good accuracy.

3.2. Impact of climate variables on winter wheat yield from 1981 to 2010

Solar radiation decreased in the Northern China Plain (NC) and the Yellow and Huai River Valleys (YH) from 1981 to 2010, but the decrease in solar radiation of this 30-year study period was only significant in the YH region (Fig. S2a). Conversely, solar radiation in Southwestern China (SW) and the Middle and Lower Yangtze Valleys (YV) showed a slight increasing trend (Fig. S2a). Significant warming trends were observed throughout the winter wheat growth periods in every region (Fig. S2b).

When all climate parameters were considered, wheat yields for both obsolete and modern cultivars decreased in all regions (Fig. 3 ALL). This is likely due to the measured increases in temperature in all regions during the wheat growing period (Fig. S2b), and the extent of yield decline was comparable to the mean temperature in the region. However, the change in yields between modern (00) and obsolete (80) cultivars for all climate parameters was region-specific. The yield decline of modern cultivars was less than that of obsolete cultivars in NC (− 0.62% for C00 vs. -2.20% for C80), YH (− 3.38% for C00 vs. -7.16% for C80), and YV (− 6.10% for C00 vs. -6.93% for C80). Conversely, for Southwestern China (SW), the yield of C80 decreased less than that of C00 (− 5.00% for C80 vs. -4.56% for C00), although the difference was not significant.

When temperature was considered alone, the relative yield change for obsolete and modern cultivars was significant in all regions (Fig. 3, Temp). The result demonstrates the negative impact of increasing temperatures on wheat yield. The relative yield change with radiation showed differences between regions and cultivars (Fig. 3 Rad). The yield trends in these four regions demonstrated that the wheat yield was positively dependent on radiation during the winter wheat growing period. Details about the results are described in the Supplementary Materials.

3.3. Contributions of cultivar renewal and agronomic management improvement to winter wheat yield change

Impacts of genotypic improvements and agronomic management practices were calculated using Eqs. (2) and (3), respectively, for each region over the 30-year period of study (Fig. 4). Cultivar renewal and improvements in agronomic management both significantly boosted yield. However, the magnitude and extent varied by factor and region. The contributions of cultivar renewal to wheat yield were all significantly different among regions. The YV benefited the most from cultivar renewal with an estimated 52.72% (1548 kg ha^{-1}) increase, significantly greater than any other regions. SW showed the second largest increase at 24.72% (937 kg ha^{-1}), followed by YH with a 17.69% (1033 kg ha^{-1}) increase. The improvement in wheat yield from cultivar renewal was the lowest in NC at 6.93% (411 kg ha^{-1}).

The improvement in wheat yield with agronomic management was greater than that from cultivar renewal in three of the four regions. The YV and SW regions showed significantly greater improvement in wheat

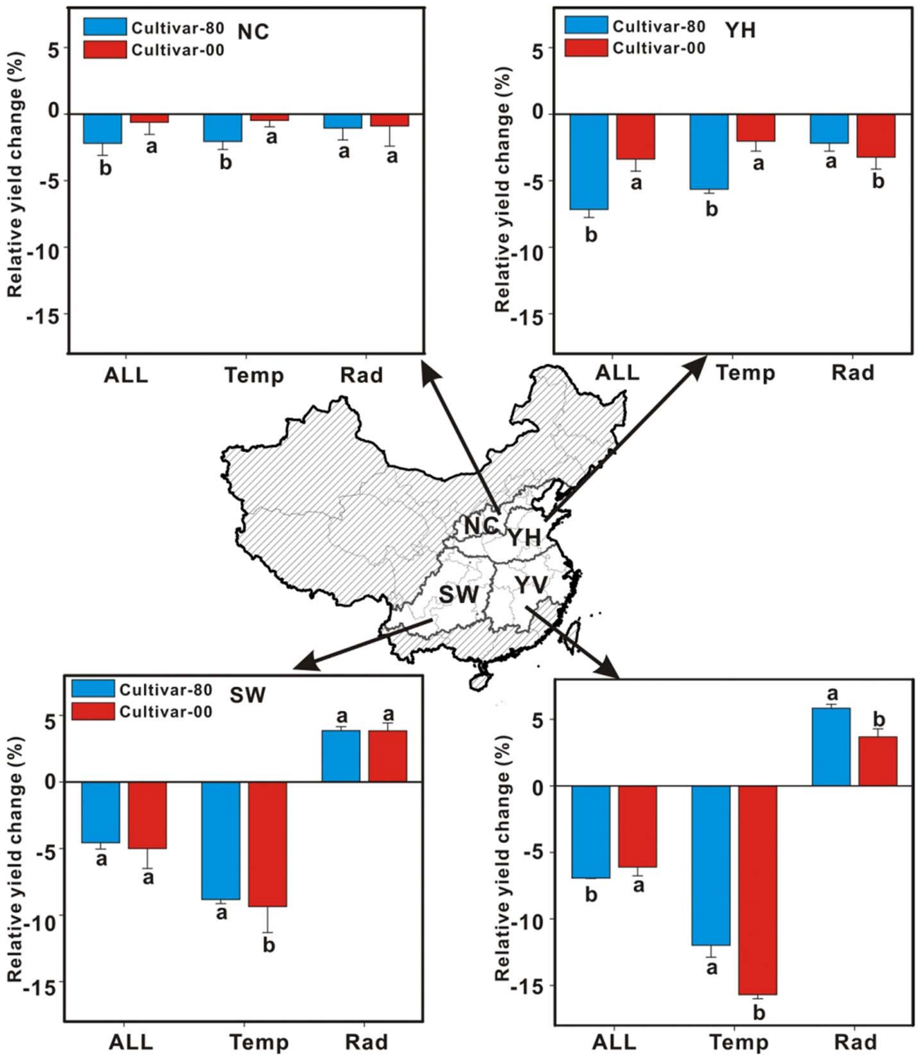

Fig. 3. Impact of all climate variables (ALL), and temperature (Temp) and solar radiation (Rad) individually, on winter wheat 30-year relative yield. The different letters above the bar indicate a significant difference ($p < 0.05$).

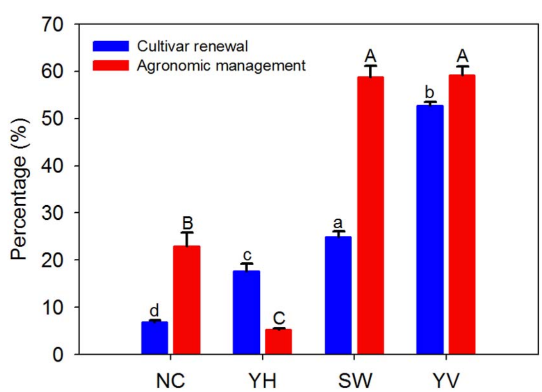

Fig. 4. Contributions (%) of cultivar renewal (blue) and agronomic management (red) to winter wheat yield change in the four regions from 1981 to 2010 calculated using Eqs. (2) and (3). The different letters above the bar indicate a significant difference ($p < 0.05$). Percent contribution of cultivar renewal (blue, Eq. (2)) and agronomic management (red, Eq. 3) to wheat yield in each region. NC, Northern China Plain; YH, Yellow and Huai River Valleys; YV, Middle and Lower Yangtze Valleys; SW, Southwestern China. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

yield with agronomic management, at improvement rates of 59.2% (2331 kg ha^{-1}) and 58.77% (1771 kg ha^{-1}), respectively. The wheat yield in NC increased 22.91% (1232 kg ha^{-1}) with agronomic management, while the lowest increase was found in YH that is a rate of 5.27% (357 kg ha^{-1}). This region was also the only region to show greater improvement with cultivar renewal than agronomic managements.

The trends of yield difference due to changes in cultivar (Y_{S3}–Y_{S1}) which can indicate the ability for the cultivar to adapt to climate change and trends in yield due to changes in management (Y_{S3}–Y_{S2}) which can show the efficiency of agronomic management to adapt to climate change are shown in Fig. S3–S4 in the Supplementary materials.

3.4. Potential yield improvements with climate-smart management

As shown in Fig. 5 there is still ample room for yield improvement by optimizing agronomic management through climate-smart management. The potential yield improvement can be determined by repeating the simulation with current winter wheat cultivars, optimum planting density, and the theoretic optimal planting date. Compared with the yield increase under current management, simulations with climate-smart management substantially increased the yield in all regions (Fig. 5). Average increases ranged from a modest 713 kg ha^{-1} yield enhancement observed in YV to 4527 kg ha^{-1} in SW (Fig. 5). The highest potential increase was observed in Southwestern China (4527 kg ha^{-1}), with an increase of 99%, significantly higher than any other region. The Northern China Plain showed an average increase of 2937 kg ha^{-1}, which was a 49% increase. The Yellow and Huai River Valleys increased to an average wheat yield of 2933 kg ha^{-1}, for a 42% increase. The lowest potential improvement was found in the Middle

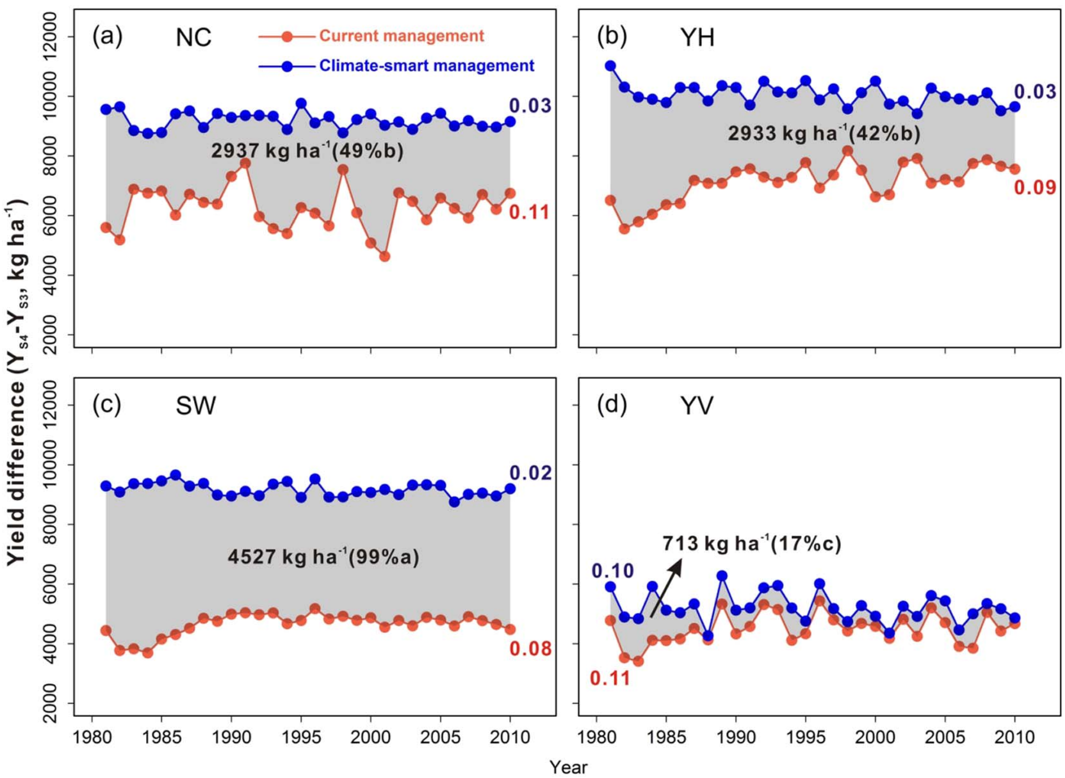

Fig. 5. Potential yield increase by implementing climate-smart management in the four regions. The grey region between the two lines is the potential yield increase, calculated as the yield difference between simulation experiments S4 and S3 in Table 3, Y_{S4}–Y_{S3}. The numbers in black indicate the average yield increase of Y_{S4}–Y_{S3} from 1981 to 2010. The numbers in brackets represent the potential ascension percentages (Eq. (4)) and the different letters following the numbers indicate a significant difference ($p < 0.05$). The numbers in blue and red represent the coefficient of variation of yield with climate-smart and current management, respectively. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

and Lower Yangtze Valleys, with only 17% (713 kg ha^{-1}), significantly lower than any other region. The coefficient of variation for yield with climate-smart management was 0.03, 0.10, and 0.02 in NC, YH, YV, and SW, respectively (blue numbers in Fig.5a–d), slightly lower than that with current management (0.11, 0.09, 0.11, and 0.08 in NC, YH, YV, and SW, respectively in red numbers in Fig.5a–d), suggesting that yield with climate-smart management is more stable.

4. Discussion

4.1. Impacts of different climate variables on winter wheat yield

In this study, the temperature during the past three decades increased in all study regions. Conversely, the trends of solar radiation during winter wheat growth period were inconsistent, with an increasing trend in southern China (SW and YV) and a decreasing trend in northern China (NC and YH) (Fig. S2). Our results of the impacts of weather on winter wheat yield agree with results from numerous other studies at a station level in the North China Plain and Jiangsu, Anhui Provinces (Bai et al., 2015; Xiao and Tao, 2014). Our results using the APSIM-Wheat Model demonstrate that the dependence of wheat yield on temperature was negative and the dependence on radiation was positive (Fig. 3 and Fig. S2). These results are in agreement with other studies. Studies have shown that there is a negative response of global wheat yield to increased temperatures (Lobell and Field, 2007; You et al., 2009), and most wheat yield impacts were driven by temperature rather than precipitation trends (Lobell et al., 2011). Li et al. (2015) found that without cultivar improvements, the yield potential of winter wheat decreased from 1981 to 2010 in the North China Plain. Further analysis indicated that negative solar radiation trends and increasing temperatures resulted in this declining yield potential. Chen et al. (2013) observed that decreasing solar radiation exerted a much greater negative impact than increasing temperature on yield potentials of winter wheat in the North China Plain from 1961 to 2003.

Temperature impacts crop phenology and yield through various mechanisms. Additional studies have suggested that the warming in the preceding decades in the North China Plain mainly occurred during the vegetative (pre-flowering) growth stage of wheat (Liu et al., 2010). Similar phenomenon has been observed in the growing season of wheat in Australia and Argentina (Sadras and Monzon, 2006). The adoption of new crop varieties can stabilize the length of pre-flowering and extend the length of the grain-filling period, which has led to increased crop yield and offset the potential impact of warming trends (Kantolic et al., 2007; Liu et al., 2010). We can also see from Fig. S1 that compared with cultivar-80, the post-flowering (grain-filling period) of cultivar-00 has been lengthened in all regions. Further analyses have shown that an earlier anthesis date caused by climate warming may result in an advancement of the grain-filling period. In that case, there was a cooling trend in the reproductive growth period in the condition of earlier anthesis compared with the unchanged condition of anthesis (Liu et al., 2010; Ludwig and Asseng, 2010; Tao et al., 2012). The new cultivars require more thermal time to complete development, which could compensate for the negative effect of climate warming while prolonging the growing period (Liu et al., 2010; McMaster et al., 2008; Tao et al., 2012).

4.2. Contribution of cultivar and management to winter wheat yield in the past three decades

The effect of cultivar and agronomic factors on crop yield has been investigated in numerous studies. The general conclusion was that adaptation options, such as the improvement in crop varieties and changes in the sowing date, could alleviate the negative effects of rising temperature and increase crop yield (Wang et al., 2012b). Studies in the

North China Plain showed that cultivar renewal during 1980–2009 contributed to yield increases by 12.2–22.6% and fertilization management contributed to yield increases by 2.1–3.6% (Xiao and Tao, 2014). In this study, we untangled the contributions of climate change, cultivar renewal, and agronomic management. The agronomic management mainly included the sowing date, the planting density, irrigation and fertilization management. The major drivers of the yield changes differed significantly between regions due to different climate, farming practices, and other socioeconomic factors, and hence so did the adaptation options (Howden et al., 2007). From the differences in drivers, we can see that the improvement of agronomic management is greater than the improvements in yield due to cultivar renewal in three regions for the past three decades (Fig. 4). The only exception is seen in the YH region, where improvements in cultivar renewal improved yields more than agronomic management. Studies have shown that the management practices such as irrigation and fertilization have been stable since the 1980s in YH and did not contribute as much to grain yield variation (Liu et al., 2010). However, significant contributions from winter wheat varietal changes to yield improvement were found in YH (Liu et al., 2010) to adapt to the significant climate change in YH compared with the other regions (Fig. S2). These may be the main reasons for the lower impact of agronomic management in YH (Fig. 4) and for the trends in yield differences observed in Fig. S3–S4.

We can see that there is still ample room for yield improvements in winter wheat in China. Implementation of climate-smart management can direct these improvements. Southwestern China would benefit the most significantly, at a value of 99%. Due to the complicated topography in SW, the effectiveness of implemented technical measures is poor. This may be the reason for the highest potential increase in yield in this region.

4.3. Uncertainty analysis and expectations

When the impacts of different climate variables on winter wheat yield were estimated, we only considered solar radiation and temperature, omitting the effects of precipitation and carbon dioxide concentration. Because the modeling environment for yield potential was under no water stress, the effect of precipitation was not considered. In this study, the CO_2 level was set constant at 340 ppm during the research period. This setting would limit the positive effects of rising CO_2 and overestimate the negative effects of climate change on wheat production (Lobell and Field, 2007; Long et al., 2006). Additionally, Zhang et al. (2013) showed that cultivar renewal and fertilization management can increase the yield but did not reduce the extent of yearly yield variation. This study mainly concentrated on the impact of the climate trends on the yield trend, and we did not consider about the yearly yield variation.

Cultivar selection is one of the most important factors affecting crop production yields. In this study, the cultivars were primarily selected based on the cultivar planted the longest within each region, but whether the selected cultivars accurately represented the preferred cultivars remains unknown. The progress in breeding led to a large number of cultivars, which made it difficult to identify a representative cultivar preference in the model. Conversely, even for one location, it is difficult to use a crop model to capture all traits of cultivar change (Li et al., 2015). This should be taken into consideration when analyzing the impact of cultivar renewal (Fig. 4) and trend of yield differences due to cultivar changes (Fig. S3).

In this study, we ignored the impact of different precipitation years on irrigation management and kept the irrigation schemes constant throughout the simulation. In fact, other improvements in agronomic management practices such as the use of no-tillage and plastic film can contribute significantly to yield; however, these were not considered in this study. We analyzed the contribution of agronomic management as a whole, but the specific contribution of individual management practices, such as the sowing date (Sun et al., 2007), irrigation (Liu et al., 2015) and fertilization (Lu et al., 2015), were not discussed in this study. This will be the subject of future research.

According to the concept of climate-smart management in this study, we should enhance the timely protective control measures to improve the accuracy of climate-smart management. Additionally, we should strengthen its impacts on reduced greenhouse gas emissions and make climate-smart management more sophisticated. These issues warrant further studies.

5. Conclusions

Farmers are faced with ever-changing challenges that must be addressed to meet the needs of society for food, feed, fuel, and fiber. This study showed that winter wheat yields showed the least decline in NC under climate change. Cultivar renewal combined with improved agronomic management boosted yields to a different extent for different regions. For cultivar renewal, yields increased 6.93%, 17.69%, 24.87%, and 52.72% in the NC, YH, SW and YV regions, respectively over the period 1981 to 2010. Agronomic management improved yields by 22.91%, 5.27%, 58.77%, and 59.20% in these regions, respectively. In general, the observed yield improvements with agronomic management were higher than those resulting from cultivar renewal for most of the wheat growing regions of China. The exception was found in the YH region, where improvements in winter wheat yield from cultivar renewal were greater than those from agronomic management. However, there is still ample room for yield improvements in winter wheat by implementing climate-smart management. The Southwestern China region would benefit the most significantly, with a potential increase of 99% due to improved investment in management. More moderate, but still significant increases were observed in NC and YH (49% and 42%, respectively). Only moderate improvements were observed in the YV region (17%). Also of note was the increased resilience of climate-smart management evidenced by the decline in the coefficient of variation (Fig. 5). These changes would provide additional benefits to farmers through greater yields, with more consistent productivity.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.agsy.2018.01.010.

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